AF-36M Airflow Rig

Technical Summary Report

U.S. Army Aviation Systems Command

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St. Louis, Missouri 63120

Prepared by:

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This report summarizes an ongoing effort by the Army to determine an appropriate method for accurately and repeatably measuring turbine engine nozzle components. It further documents the effort expended to establish an Industry Standard method of determining the performance characteristics of these components which may be correlated between manufacturing and test facilities based on measuring their Effective Flow Area (EFA) as opposed to their Geometric Flow Area (GFA).

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AF-36M AIRFLOW RIG

TECHNICAL SUMMARY REPORT

1987

U.S. ARMY AVIATION SYSTEMS COMMAND

4300 Goodfellow Boulevard
St. Louis, Missouri 63120

Prepared by:

TECHNASSOCIATES, INC.

1700 Rockville Pike
Rockville, Maryland 20852

AF-36M AIRFLOW RIG
TECHNICAL SUMMARY REPORT

1987

CONTRACT DAAK50-83-C-0029

BACKGROUND

This project resulted from prior investigations of the difficulties in procuring replacement parts for turbine engines from different sources with sufficient tolerance limits to enable rebuilt engines to meet performance limits on first test.

TOLERANCE FACTORS

In a helicopter turbine engine, the performance envelope for power, temperature, and fuel consumption is extremely vulnerable to small variations in turbine nozzle and rotor factors under critical emergency operations. At the engineering design level, the engine design limits are predicated on the ability of the manufacturing facility, the storage and transportation facilities and field operations to deliver to the pilot the rated performance under normal operational conditions. When faced with a military or operational emergency, the pilot may force the aircraft to the limits of the engine performance envelope on the assumption that he has been made aware of the rated limits. However the actual limits on the specific engine in his aircraft, whether new, repaired or rebuilt, may not fall within the expected range, due to accumulated tolerances incurred in the life cycle history of that engine, and loss of pilot and/or aircraft may be incurred.

GFA vs EFA

One of the major problems in determining the suitability of a nozzle part for original or replacement usage had been the use of geometric methods of determining the acceptability of a nozzle or other engine part. Among the various manufacturers of turbine engines and replacement parts, there were as many methods of

measuring the geometric flow area as there were sources. In fact the procurement specifications referred to Geometric Flow Area as the acceptance criteria. For complex parts such as small turbine engine blades and nozzle configurations, the measurement by physical probing or optical planimeter methods is extremely difficult.

In actual engine application, the flow pattern through the components is seldom directly related to the simple GFA of individual parts but depends on how the upstream and downstream flow interacts with the particular component. Thus the use of GFA is only correlated with mass flow parameters for very simple shapes measured in a carefully configured test environment. This has been accomplished for certain standardized shapes such as circular orifices and other nozzles with elliptical profiles. In particular the relation between GFA and Effective Flow Area (EFA) has been studied by various organizations for nozzles of the type with elliptical profiles of certain proportions and carefully controlled cylindrical throat dimensions. These ASME nozzles have become widely accepted as standards and have been used in this program.

The principal problem encountered in engine rebuild is the amount of time and cost associated with multiple disassembly and reassembly with different nozzle parts to attempt to bring a completed turbine engine into final hot cell performance specifications. What had been experienced at rework facilities was the fact that there was not a reliable relationship between the GFA marked on a part and its effect on the performance of the completed engine. While manufacturers and rework facilities had developed various methods for choosing parts within GFA limits, there did not appear to be any uniform way to correlate their data to actual performance. Various methods to compare production parts to so-called "relative masters" were being used,

but the results between sources and rework facilities were uncertain.

PRIOR CONTRACT EFFORTS

The U.S. Army Aviation Research and Development Command (AVRADCOM now AVSCOM) issued a contract to Technassociates Inc. in 1981 to provide "standards" capable of verifying and/or correlating airflow measurements between manufacturers and Army equipment used to obtain the EFA of turbine engine nozzles. It was organized into three phases: Procurement of Hardware (ASME standard nozzles); Data Collection; and Correlation and final report.

SUMMARY OF PRIOR RELATED WORK

During Phase I three ASME airflow nozzles having nominal throat diameters of 2in., 3in. and 5in. were procured. These nozzles were measured at an inspection facility, Advanced Quality Assurance, Inc. (AQA), in San Jose, whose reference standards are traceable to the National Bureau of Standards. They were also measured at the Calibration Laboratory at Corpus Christi Army Depot. The results of both sets of measurements indicated that the nozzles fell within the tolerance limits set forth in "Fluid Meters" Sixth Edition published by ASME 1971. Measurements at AQA also indicated that the elliptical approach contours of the nozzles followed the parameters for the equation for ellipses meeting the range established for "long-radius" nozzles in "Fluid Meters". No tolerances for the contour surfaces have been established by ASME, but the actual contour does not significantly affect measurements made using these nozzles as long as the approach surface is smooth.

The final values for the diameters of the ASME nozzles used in subsequent phases were 2.0011, 2.999, and 5.0004 inches.

PHASE II SUMMARY

The principal effort in Phase II was devoted to obtaining readings of the EFA for each of the three ASME standard nozzles on the airflow rigs at CCAD, Allison (Indianapolis), AVCO Lycoming (Stratford), and GE (Lynn). Due to the limitations of the facilities at GE, the 5 inch nozzle could not be run. A corollary effort was made to obtain an understanding of the principles of operation of each test facility, the method of calibration, and the production measurement procedures in order to develop the recommendations required in Phase III.

A summary of the results obtained in Phase II can be seen in Table III-1 which is taken from the Phase II report. The EFA's computed from the runs on the original Wooley airflow rig at CCAD were obtained using an equation derived during Phase II, which reflects the unique physical parameters of the Wooley rig and the applicable fluid flow equations. The use of this modified equation yielded improved values for the EFA of the ASME nozzles compared to the linear approximations used in production testing.

The CCAD Wooley rig data indicate a large variation from the EFA measurements of the same standard nozzles at all of the other facilities. The variation between readings at the other facilities fell between +/- 0.75% and 1.78%. With Wooley rig data included, the variation is between +/- 4.6% to 7.24%.

PHASE III SUMMARY

The effort in Phase III was devoted mainly to the analysis of the data and to correcting the readings taken at each facility for possible variations due to barometric pressure, temperature, or Reynolds number differences. The combined influence of pressure drop and temperature leading to a determination of Reynolds number can be seen in Table III-2. A separate adjustment for the thermal expansion of the nozzle

throat diameter was computed as shown in Table III-4. The final adjustment to the coefficient of discharge is shown in Table III-5.

The comparison between the adjusted EFAs of the ASME nozzles and the EFA values obtained or reported at each facility is shown in Table III-6. Finally the "correlation" between facility measurements, with and without CCAD data, is provided in Table III-7. An error analysis was performed on each set of data and a comparison of the estimated error at the 95% confidence limit compiled in Table III-8. Recommendations for improving the accuracy and reliability of the data were included in the report.

Based on the total project efforts it was concluded that the airflow rig of the type used at Allison would be a valuable addition to the facilities at CCAD.

Facility	d/D	Upstream pressure PSIA.	p in. H_2O	T °F	Exit Velocity	Reynolds Number
Corpus Christi	0.25	16.67	51	170	491 ft/sec	614,000
Allison	0.08	14.88	5	80	150 ft/sec	213,000
AVCO Lycoming	0.2	15.78	30	150	379 ft/sec	485,000
GE	0.27	32	480	148	1066ft/sec	1,670,135

Table III-2. Reynolds Number Parameters for 3" ASME Nozzle

Using these values and Eq. II-III-12 we obtain the following values for C_d:

Corpus Christi	.9932
Allison	.9935
AVCO	.99315
GE	.9968

The value of C_d for Allison does not appear to fit the trend established by the other values. Examination of the parameters in Table III-2 indicates that d/D falls outside of the valid range for Eq. II-III-12. In addition, the value for D, the pipe diameter, is 36 inches in the case of the AF-36 rig. On both counts it appears that Eq. II-III-12 cannot be used for the Allison conditions.

Eq. II-III-42 which is given in the Errata sheet issued in 1974 for "Fluid Meters" has the following form:

$$\text{(Eq. II-III-42)} \quad C = 0.9975 - 0.00653 \left(\frac{1,000,000}{R_d} \right)^a$$

$$a = .5 \text{ for } R_d < 10^6$$
$$= .2 \text{ for } R_d > 10^6$$

Using this equation and the data from Table III-2 we obtain:

	C_d
Corpus Christi	.9892
Allison	.983
AVCO	.988
GE	.992

Table III-3. Coefficient of Discharge, 3 inch nozzle

While these values are lower than those derived using Eq. II-III-12, they are internally consistent with the data.

These computations indicate that the Coefficient of Discharge will effect the computation of EFA by about 1% over a range of Reynolds numbers from approximately 200,000 to 1,700,000. Expressed in terms of the observed pressure drop, the variation ranges from 5 inches of water to over 400 inches of water.

While the data obtained on this project indicates potential measurement or observation errors in the range of 1 to 8%, it appears that measurement of EFA in a "low speed" rig can be related to "high speed" measurements by an adjustment to the reported EFA value for the Reynolds number applicable to the particular rig and test conditions.

Nozzle Diameter (70°F)	2.0011	2.9999	5.0004
Temperature			
70	3.1450	7.0681	19.6381
80	3.1458	7.0698	19.6428
90	3.1465	7.0715	19.6475
100	3.1473	7.0732	19.6522
110	3.1480	7.0749	19.657
120	3.1488	7.0766	19.6616
130	3.1495	7.0783	19.6664
140	3.1503	7.08	19.6711
150	3.1510	7.0817	19.6758
160	3.1518	7.0835	19.6805
170	3.1525	7.0851	19.6852
175	3.1529	7.0859	19.6876
180	3.1533	7.0868	19.6899

TABLE III-4. Nozzle Area (GFA) vs. Temperature

	2"		3"		5"	
	R_d	C_d	R_d	C_d	R_d	C_d
Corpus Christi	419,000	.987	614,000	.989	743,000	.990
Allison	142,000	.980	213,000	.983	355,000	.987
AVCO	318,000	.986	485,000	.988	585,000	.989
GE	1,344,000	.991	1,670,000	.992	-	-

(1) $C_d = 0.9975 - 0.00653 \left(\frac{1,000,000}{R_d} \right)^a$ Eq. II-III-42

$a = .5$ for $R_d < 10^6$
$= .2$ for $R_d < 10^6$

TABLE III-5. Coefficient of Discharge(1) for ASME Nozzles

Facility	C_d	Temp. Airstream	Nozzle Temp (1)	GFA (1)	Computed EFA (4)	Reported EFA	Difference % EFA (4)
				"2"			
Corpus Christi	.987	170	150	3.1510	3.1100	2.8405	- 8.7%
Allison	.980	82	80	3.1458	3.0829	3.0768	- 0.2%
AVCO	.986	165	150	3.1510	3.1069	3.0695	- 1.20%
GE	.991	153	138	3.1501	3.1228	3.1455 (3)	+ 0.73%
				"3"			
Corpus Christi	.9892	170	150	7.0817	7.0052	7.334	+ 4.69%
Allison	.983	80	80	7.0698	6.9496	6.918	- 0.45%
AVCO	.988	150	135	7.0792	6.9942	6.952	- 0.6%
GE	.992	148	133	7.079	7.0224	7.007 (2)	- 0.2%
				"5"			
Corpus Christi	.990	160	140	19.6711	19.4744	20.502	+ 5.28%
Allison	.987	80	80	19.6428	19.3874	19.313	- 0.38%
AVCO	.989	138	130	19.6664	19.4501	19.166	- 1.5%

TABLE III-6. Comparison of Computed EFA (corrected for test) vs. Reported EFA

Reported EFA

Facility	2 inch	3 inch	5 inch
Corpus Christi	2.8405	7.334	20.502
Allison	3.0768	6.918	19.313
AVCO	3.0695	6.952	19.166
GE	3.1455	7.007	
Mean, with CCAD	3.0331	7.0528	19.6603
Standard Deviation	0.1151	0.1655	0.5982
95% Confidence Limit	± 0.2255	± 0.3243	± 1.1725
% of Mean	± 7.44%	± 4.59%	± 5.96%
Mean, Less CCAD	3.0973	6.958	19.2395
Standard Deviation	0.0342	0.0367	0.0735
95% Confidence Limit	± 0.0671	± 0.0719	0.1441
% of Mean	± 2.17%	± 1.03%	0.75%

Table III-7. Correlation Between Facility Measurements

		95% Confidence limits (%) (includes CCAD)	Error (%)
Corpus Christi	2 inch	7.44%	8.7%
	3 inch	4.59%	4.69%
	5 inch	5.96%	5.28%
		95% Confidence Limit (%) (excludes CCAD)	
Allison	2 inch	2.17%	0.2%
	3 inch	1.03%	0.45%
	5 inch	0.75%	0.38%
AVCO	2 inch	2.17%	1.2%
	3 inch	1.03%	0.6%
	5 inch	0.75%	1.5%
GE	2 inch	2.17	0.73%
	3 inch	1.03	0.2%

TABLE III-8. Comparison of Absolute Error to 95% Confidence Limit in %

SUMMARY OF
TURBINE ENGINE NOZZLE MEASUREMENT AND CORRELATIVE
QUALITY FORUM (1981)

In 1981 a meeting of the Quality Forum was held at CCAD. Attendees included representatives from AVRADCOM, CCAD and Technassociates. The purpose of the Forum was to review the original problems which were to be addressed by this project and to discuss the findings and recommendations.

The visuals used as a basis for discussion are presented in the following section. The significant results of the Forum are summarized under the heading of "Follow-on Program" as shown on the last two visuals. They reflect the immediate goals which formed the basics of the current contract.

It was recommended that:

- CCAD acquire a commercial airflow rig.

  The airflow rig produced under this subject contract is similar to the AF-36 encountered in the Allison installation in the prior study. However, it has been considerably enhanced by the addition of a second blower in order to provide a larger airflow range for measurement of nozzles up to 9 inches in equivalent ASME throat diameter.

- Install at CCAD and Train Personnel

  The modified AF-36M rig has been installed at CCAD and production staff and calibration laboratory staff have been involved in its initial installation, calibration and operation.

- Measure CCAD XREF Nozzle EFAs

  Under the subject contract, the series of ASME standard nozzles provided with the AF-36M rig constitute the new reference standards for measurement of the EFA of production parts. The AF-36M, when calibrated, has the ability to provide accurate EFA readings directly without the use of "XREF" relative masters, of course, the EFA of relative masters can also be accurately measured.

- Correlate to Wooley Rig

  Since the prior studies showed that the Wooley rig is not capable of measuring EFAs to the necessary degree of absolute accuracy, there is no need to continue its use. In particular, "relative masters" previously used in the Wooley rig operation can now be measured on the AF-36M against EFA standards if there is a need to review older data against newer production runs.

FOLLOW-ON PROGRAM OVERVIEW

1. Set Tolerance Limits for Nozzles
2. Product Specifications/Standards
3. Extended Operation vs "cold" EFA - EFA Stability = ?
4. Engine Teardown/Rebuild vs Compressor Variation
5. Reliability/Predictability of Engine Performance Envelope.

These topics presented at the Quality Forum set forth the long term goals of the program. The ultimate objective of this program is to enable the procurement of turbine engine (nozzle) parts to specifications which enable an engine to be assembled or rebuilt such that it meets performance envelope specifications on

first attempt. Recognizing that a turbine engine is a complicated system, it is nevertheless necessary to be able to set tight tolerance limits on each component in order to predict the effect of each individual component on the total engine performance.

1. With the availability of ASME standard nozzles and the AF-36M, CCAD is now in a position to explore the relation between an accurately known EFA of a nozzle and its effect on engine performance. With some production experience, CCAD will be able to specify tolerance limits which will enable useful acceptance limits for replacement nozzle components to be set.

2. A follow-on task is to introduce these tolerance limits into the Product Specification/Standards channels such that parts from multiple sources can be obtained with assurance that they will meet production requirements with negligible rejects or rework.

3. One question which remains to be answered is whether measurements made at low airflow velocity and temperature can be used to predict the operation of the nozzle in actual "hot" operation. For parts which have not been severely bent or otherwise stressed, the "hot" EFA should be well correlated with "cold" measurements. Parts which have not been stress relieved or which have been brought into tolerance by extensive rework may exhibit considerable change between cold and hot performance. Further investigation is recommended.

4. In the past, engine rebuilders have developed empirical methods of varying components in the different stages of a turbine engine to get a particular engine to meet specifications. The danger in these procedures is that the

margin of safety between the normal performance specifications and the demand for performance under emergency conditions is not known. When an engine installed in an operational aircraft is called upon to operate at or above the performance envelope limits, the effects of random combinations of components may cause some engines to fail to meet the demand even though they apparently met "hot cell" specifications.

With the effects of accurately measured components on overall engine performance known, it should be possible to develop procedures for rebuilding the different stages which follow the theoretical or engineering design criteria in a predictable manner.

5. Finally, one objective of the program will have been met if the margin of safety at the nominal performance envelope limits of engines which are ready for installation in operational aircraft is known. If this confidence level can be obtained at the first complete assembly of the engine, a major advance will have been achieved. If the total number of rebuild cycles during the life of the engine is reduced, significant cost and time savings will have been realized.

It is recommended that these program objectives be pursued in each of the required areas.

TURBINE ENGINE NOZZLE MEASUREMENT AND CORRELATION QUALITY FORUM

PROGRESS 1981

TECHNASSOCIATES, INCORPORATED

OBJECTIVES:

- ESTABLISH QUALITY MANAGEMENT PROGRAM
- REDUCE THE COST OF QUALITY
- MAKE AVRADCOM THE STANDARD FOR QUALITY

PROBLEM AREAS — 1980 FORUM

UNRELIABLE ENGINE LIFE · PERFORMANCE ENVELOPE

- HIGH-COST MULTIPLE ASSEMBLY/DISASSEMBLY TO YIELD 'ACCEPTABLE' ENGINES
- POOR CORRELATION BETWEEN GFA-BASED PART NUMBERS AND TEST-CELL ENGINE PERFORMANCE
- THE GFA — EFA CONTROVERSY
- IMPACT OF NOZZLE AREA VARIANCES ON OVERALL ENGINE PERFORMANCE

RECOMMENDATIONS — 1980 FORUM

- AIRFLOW NOZZLES TO DETERMINE EFA
- CORRELATE ALLISON, LYCOMING & CCAD RIGS
- USE ASME STANDARD NOZZLES
- EVALUATE AIRFLOW RIGS
- DEVELOP AIRFLOW-BASED (EFA) SPECIFICATIONS
- UPGRADE CCAD AIRFLOW MEASUREMENT CAPABILITY

THE AVRADCOM—TECHNASSOCIATES CONTRACT

PHASE I

- LOCATE, INSPECT AND PROCURE 3 ASME NOZZLES
- SURVEY 3 MANUFACTURERS AND CCAD
- PROCURE ADAPTERS

PHASE II

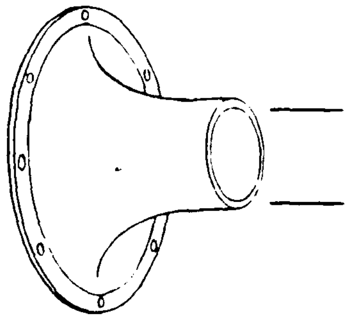
- FLOW ASME NOZZLES AT EACH FACILITY
- ACQUIRE AIRFLOW DATA FOR CORRELATION

PHASE III

- ANALYZE DATA

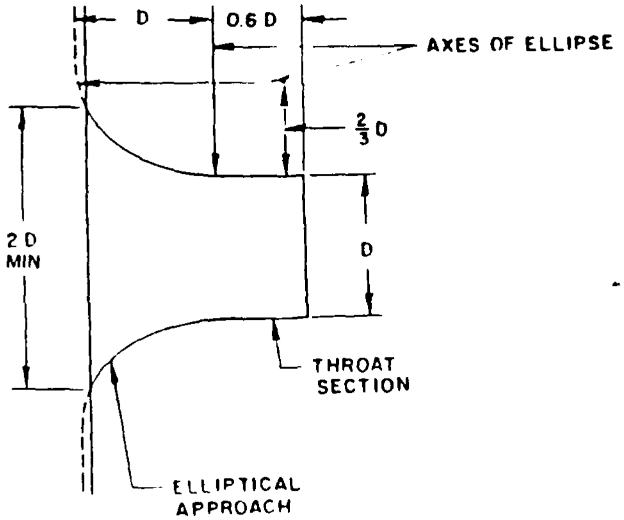
PHASE I

ORDERED 3 ASME NOZZLES FROM
DELTA—T CO — SANTA CLARA



NOMINAL THROAT DIAMETERS 2, 3, 5 INCHES

ASME NOZZLE SPECIFICATIONS



- LONG RADIUS ELLIPTICAL CONTOUR EQUATION

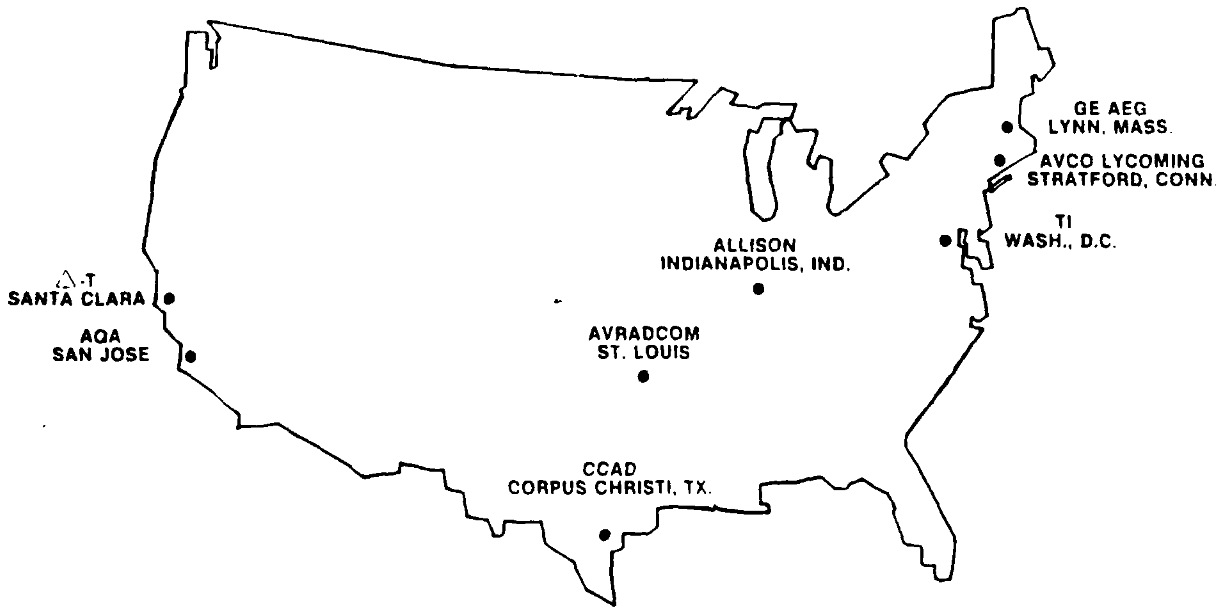
  $$x^2 + \frac{4}{9} y^2 = \frac{4}{9} D^2$$

- TOLERANCES — THROAT SECTION TAPER:
  - −0.001 IN. FOR DIA. ≦ 3.00 IN.
  - −0.0015 IN. FOR 3.01 ≦ DIA. ≦ 6.00 IN.

  OUT-OF-ROUND:
  - ±0.002 IN. FOR DIA. ≦ 3.00 IN.
  - ±0.003 IN. FOR 3.01 ≦ 6.00 IN.

- NO ASME TOLERANCE FOR ELLIPTICAL SECTION

PHASE I SURVEY FACILITIES



PHASE I
INSPECTION OF ASME NOZZLES

- ADVANCED QUALITY ASSURANCE INC. (AQA), SAN JOSE
- CCAD CALIBRATION LABORATORY

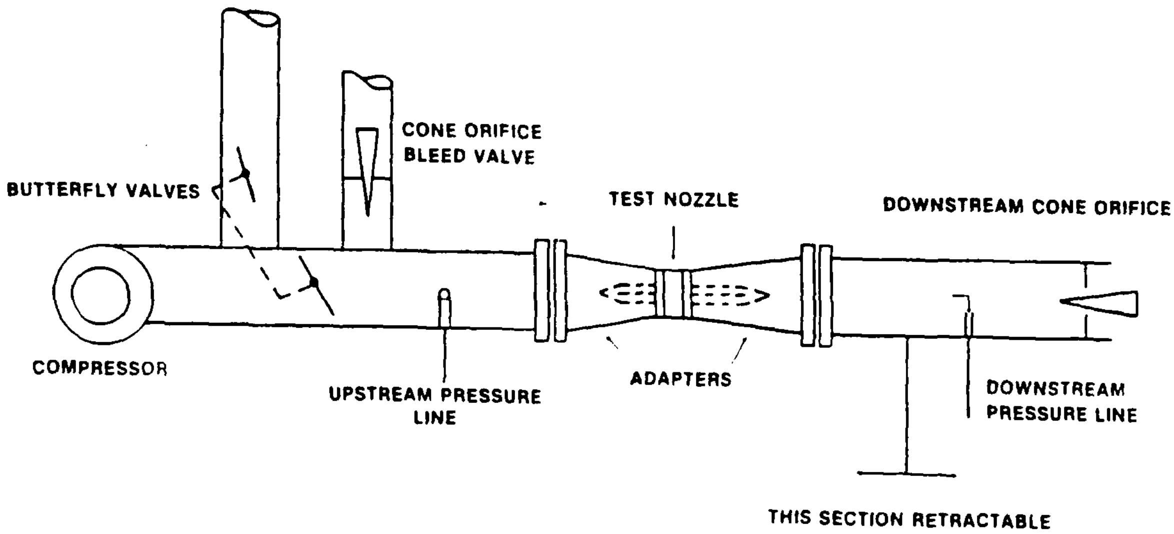
AVERAGED RESULTS

DIAMETER	GFA AT 70° F
2.0011	3.1450 IN. SQ.
2.999	7.0681
5.0004	19.6381
MEASUREMENT ERROR ± 0.0003 IN.	GFA ERROR ± 0.0006 IN. SQ.

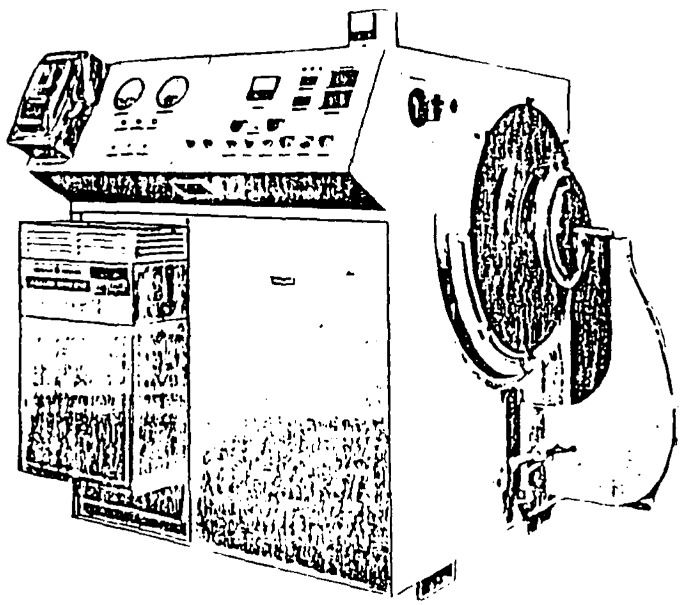
PHASE I FACILITIES

CORPUS CHRISTI ARMY DEPOT

WOOLEY AIR FLOW RIG



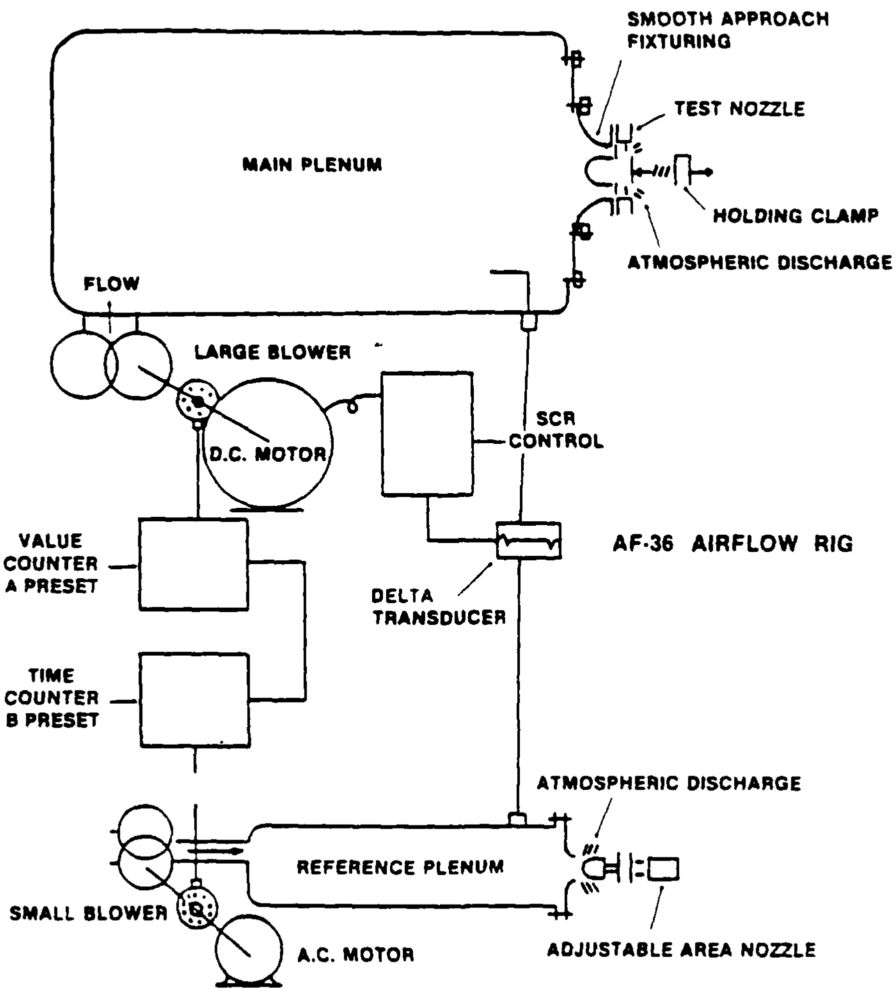
ALLISON



AF-36
AIRFLOW RIG

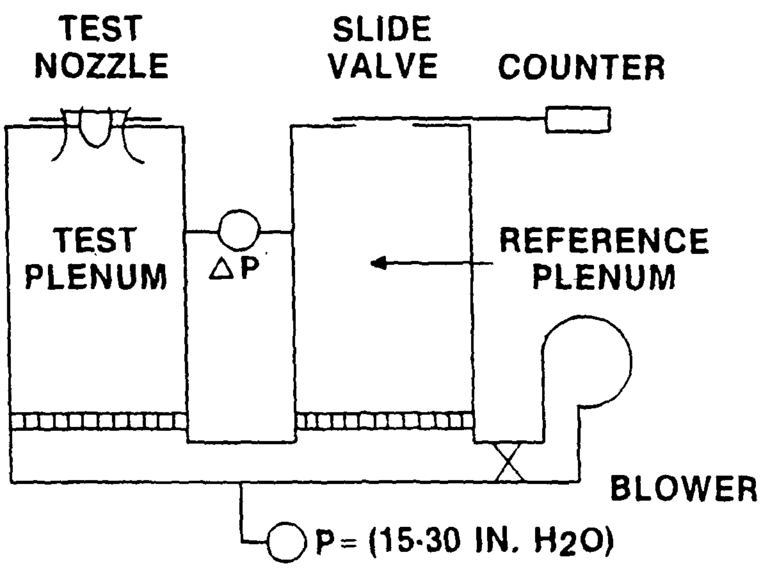
PHASE I FACILITIES

ALLISON

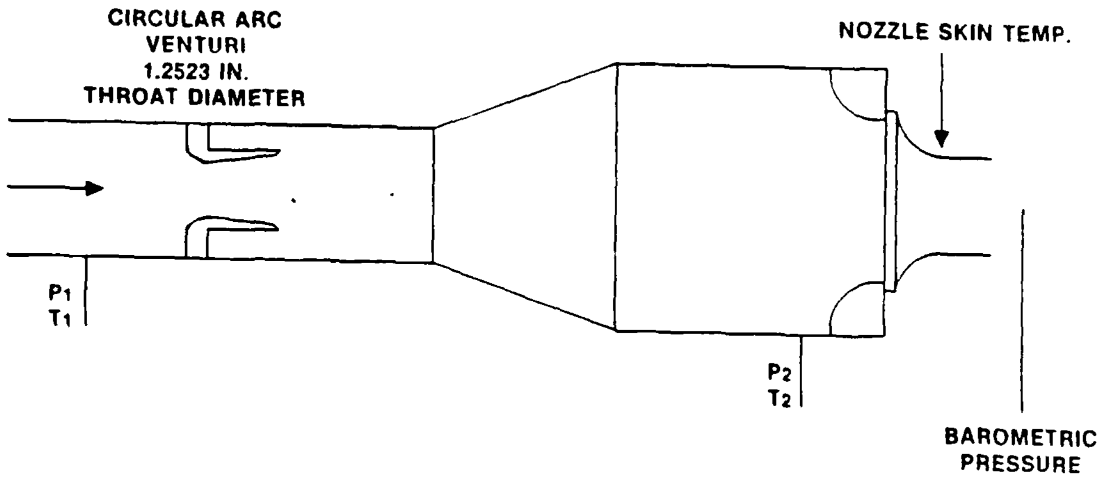


PHASE I FACILITIES

LYCOMING LOW SPEED EFA MEASURING SYSTEM



GE, AEG


CIRCULAR ARC
VENTURI
1.2523 IN.
THROAT DIAMETER
NOZZLE SKIN TEMP.
P1
T1
P2
T2
BAROMETRIC
PRESSURE

TECHNASSOCIATES INCORPORATED

PHASE II ACQUIRE DATA

TEST PROCEDURES

- CALIBRATE RIG — STANDARD PROCEDURES
- MAKE 3 TEST RUNS ON 3 ASME NOZZLES USING STANDARD OPERATING PROCEDURES
- RANDOM SEQUENCES OF NOZZLES, OPERATORS, TIME OF RUN
- COPY LOCAL DATA LOGS

PHASE II ACQUIRE DATA

AT CCAD
CALIBRATION

- INSERT X REFERENCE NOZZLE
- STABILIZE RIG FOR ½ HOUR
- ZERO UPSTREAM AND DOWNSTREAM MANOMETER SCALES TO 10" H_2O
- * SET UPSTREAM PRESSURE TO SPEC.
- * SET DOWNSTREAM PRESSURE TO # + 2.5" H_2O
- RECORD Pup (ref) AND Pdn (ref)

* THESE VALUES ARE SET USING CONE ORIFICE VALVES

PHASE II ACQUIRE DATA

AT CCAD
PRODUCTION PROCEDURES

- CALIBRATE RIG EVERY 5 NOZZLES w Xref.
- SUBSTITUTE TEST NOZZLE FOR Xref.
- DO NOT CHANGE CONTROLS
- RECORD Pup AND Pdn
- RECORD AREA OF TEST NOZZLE BY

$$X_{ref} \frac{P_{up}(ref) - P_{dn}(ref)}{P_{up} - P_{dn}}$$

NOTE: Xref HAS BEEN ASSUMED (BY CCAD) TO BE GFA

INITIAL RESULTS AT CCAD

Xref NOZZLE	GFA*	GFA ASME NOZZLE	COMPUTED GFA **	ERROR
T-63 - 1st STAGE	3.45	3.145	2.757	12.3%
" 3rd STAGE	9.00	7.069	5.845	17.3%
" 2nd STAGE	16.9	19.63	25.896	31.9%

* FROM CCAD SPEC. SHEET

** FROM CCAD EQUATION

REVISED EQUATION FOR WOOLEY RIG

INITIAL EQUATION CCAD

$$Ax = Aref \frac{\Delta Pref}{\Delta Px}$$

REVISED EQUATION

$$Ax = Aref \sqrt{\frac{Px}{Pref} \frac{\Delta Pref}{\Delta Px}} \longrightarrow Aref \left(\frac{\Delta P(ref)}{\Delta Px}\right)^{0.6}$$

APPROXIMATION

Px AND Pref IN PSIA

RESULTS AT CCAD USING REVISED EQUATION

Xref NOZZLE	GFA	GFA ASME NOZZLE	COMPUTED GFA (xxx)	ERROR
T-63 1st STAGE	3.45	3.145	3.1088	1.15%
3rd STAGE	9.00	7.069	7.3408	3.84%
2nd STAGE	16.9	19.63	20.555	4.7%

xxx REVISED EQUATION

PHASE II ACQUIRE DATA

OBSERVATIONS AT CCAD

UNSTABLE READINGS

- SMALL GFAs < 3.5 IN. SQ.
- EXTERNAL WIND CONDITIONS
- DOWNSTREAM CONE ORIFICE SETTINGS TOO CLOSE

LONG SET-UP AND EXCHANGE CYCLE

NO ABSOLUTE GFA STANDARDS

GFA VS EFA NOT RESOLVABLE

WOOLEY RIG CANNOT MEASURE GFA OR EFA OF PARTS OF UNKNOWN SIZE

PHASE II ACQUIRE DATA

DETROIT DIESEL ALLISON

CALIBRATION

- OBTAIN DIGITAL READINGS FOR REFERENCE BLOWER AND MAIN BLOWER USING SERIES OF ASME NOZZLES

PRODUCTION

- FLOW PRODUCTION PART
- RECORD MAIN BLOWER DIGITAL READING TO MATCH REFERENCE PRESET
- APPLY LINEAR INTERPOLATION TO OBTAIN GFA
- APPLY C_d TO OBTAIN EFA

RESULTS AT ALLISON

AVRADCOM ASME NOZZLE	NOM. EFA*	ALLISON EFA	RELATIVE ERROR
2 IN. DIA.	3.110	3.077	1.1%
3 IN. DIA.	6.998	6.918	1.1%
5 IN. DIA.	19.439	19.313	0.65%

* Cd = 0.99

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PHASE II ACQUIRE DATA

DETROIT DIESEL ALLISON AF-36 RIG

OBSERVATIONS

- CALIBRATION USES ASME NOZZLES DIRECTLY
- PRODUCTION CYCLE — 2-3 MIN. PER PIECE
- REPEATABILITY EXCELLENT
- LOW NOISE LEVEL
- RESPONDS TO EFA
- PRECISION AND ACCURACY GOOD

PHASE II ACQUIRE DATA

AVCO LYCOMING

CALIBRATION

- ESTABLISH EFA VS SLIDE VALVE COUNTS USING CIRCULAR APERTURE PLATES
- RUN ASME MASTER NOZZLE
- ESTABLISH CORRECTION FACTOR TO ADJUST COUNTS TO ASME MASTER VALUE

PRODUCTION

- SET SYSTEM PRESSURE (15-30 IN. H_2O)
- MOUNT TEST PIECE
- ADJUST SLIDE TO ZERO Δp
- RECORD EFA FROM COUNTER AND CORRECTION FACTOR

RESULTS AT AVCO LYCOMING

AVRADCOM ASME NOZZLE	NOM. EFA*	AVCO LYCOMING EFA	RELATIVE ERROR
2 IN. DIA.	3.110	3.0695	1.3%
3 IN. DIA.	6.998	6.952	0.66%
5 IN. DIA.	19.439	19.166	1.4%

* Cd = 0.99

PHASE II ACQUIRE DATA

OBSERVATIONS AVCO LYCOMING

- 2-STEP CALIBRATION PROCEDURE
  - ASME NOZZLES FOR DISCRETE POINTS
  - CIRCULAR ORIFICE PLATES FOR INTERPOLATION
- SLIDE VALVE APERTURE IN PARALLEL PLENUM
  - POTENTIAL FOR SHIFT IN READOUT SYSTEM
- SOME VARIATIONS DAY-TO-DAY
- PRECISION AND ACCURACY GOOD
- RESPONDS TO EFA
- PRODUCTION CYCLE 15-30 MIN/PIECE

PHASE II ACQUIRE DATA

G.E. AEG

- CALIBRATION — IN-LINE WITH PRODUCTION RUNS
  - — ASME CIRCULAR ARC VENTURI
    ESTABLISHES MASS FLOW TO TEST PLENUM
- PRODUCTION
  - — 5-1 POUND UPSTREAM PRESSURE INCREMENTS
    ESTABLISH CHOKED FLOW 30-50 PSIA
  - — OPERATOR RECORDS
    BAROMETRIC PRESSURE
    VENTURI INLET PRESSURE
    PLENUM PRESSURE
    TEMP. VENTURI INLET
    TEMP. PLENUM PRESSURE
  - — COMPUTER PRINTS OUT
    FLOW FUNCTION
    EFA
    ETC.

PHASE II ACQUIRE DATA

RESULTS G.E. AEG (AIRCRAFT ENGINE GROUP)

AVRADCOM ASME NOZZLE	NOM EFA.*	GE EFA	RELATIVE ERROR
2 IN. DIA.	3.110	3.1325	0.7%
3 IN. DIA.	6.998	7.007	0.13%

* Cd = 0.99

ADJUSTMENTS TO RAW DATA

- BAROMETRIC PRESSURE
  - CALIBRATION PROCEDURES AT CCAD, ALLISON, LYCOMING REFERENCE 'STANDARD NOZZLES'
  - GE RIG CALIBRATES EXIT PRESSURE TO STANDARD ATMOSPHERE
- $\triangle$p DIFFERENCES
  - EQUATIONS FOR REYNOLDS NUMBER AND COEFFICIENT OF DISCHARGE INCORPORATE $\triangle$p
- TEMPERATURE DIFFERENCES
  - REYNOLDS NUMBER INCORPORATES DENSITY AND VISCOSITY
  - ASME NOZZLE EXPANSION

COEFFICIENT OF DISCHARGE

	2"		3"		5"	
	R_d	C_d	R_d	C_d	R_d	C_d
CORPUS CHRISTI	419,000	.987	614,000	.989	743,000	.990
ALLISON	142,000	.980	213,000	.989	355,000	.987
AVCO	318,000	.986	485,000	.988	585,000	.989
GE	1,344,000	.991	1,670,000	.992	—	—

$$C_d = 0.009975 - 0.00653 \left(\frac{10^6}{R_d}\right)^a$$

EQ. II-III-42

"FLUID METERS"

ASME NOZZLES

$a = .5$ FOR $R_d < 10^6$

$= .2$ FOR $R_d < 10^6$

PHASE III ANALYSIS

SUMMARY RESULTS

		AVRADCOM ASME EFA*	REPORTED EFA	DIFFERENCE % EFA
2 IN. DIA	CORPUS CHRISTI	3.1100	2.8405	− 8.7%
	ALLISON	3.0829	3.0768	− 0.2%
	AVCO	3.1069	3.0695	− 1.20%
	GE	3.1228	3.1455	+ 0.73%
3 IN. DIA.	CORPUS CHRISTI	7.0052	7.334	+ 4.69%
	ALLISON	6.9496	6.918	− 0.45%
	AVCO	6.9942	6.952	− 0.6%
	GE	7.0224	7.007	− 0.2%
5 IN. DIA.	CORPUS CHRISTI	19.4744	20.502	+ 5.28%
	ALLISON	19.3874	19.313	− 0.38%
	AVCO	19.4501	19.166	− 1.58%

* CORRECTED FOR TEMPERATURE OF ASME NOZZLE AT TEST SITE

CORRELATION BETWEEN FACILITY MEASUREMENTS

	2″	3″	5″
MEAN, WITH CCAD	3.0331	7.0528	19.6603
STANDARD DEVIATION	0.1151	0.1655	0.5982
95% CONFIDENCE LIMIT	± 0.2255	± 0.3243	± 1.1725
% OF MEAN	± 7.44%	± 4.59%	± 5.96%
MEAN, LESS CCAD	3.0973	6.958	19.2395
STANDARD DEVIATION	0.0342	0.0367	0.0735
95% CONFIDENCE LIMIT	± 0.0671	± 0.0719	± 0.1441
% OF MEAN	± 2.17%	± 1.03%	± 0.75%

PHASE III ANALYSIS

FACILITY CAPABILITIES (TOLERANCE)

INCLUDES ± 1% TOLERANCE FOR Cd (PER ASME)

	2″ DIA.	3″ DIA.	5″ DIA.
CCAD	± 9.7%	± 5.7%	± 6.3%
ALLISON	± 2%	± 2%	± 2%
LYCOMING	± 2.2%	± 2%	± 2.5%
G.E.	± 2%	± 2%	

PHASE III RECOMMENDATIONS

GE
- RECALIBRATE FLOW/INSTRUMENT COMPONENTS TO RESOLVE $C_d > 1.0$

AVCO LYCOMING
- RECALIBRATE INSTRUMENTATION
- RECALIBRATE AVCO HIGH-SPEED RIG
- RESOLVE SHIFTS IN CORRECTION FACTORS

ALLISON
- USE AF-36 CALIBRATION DATA FROM 2 ASME NOZZLES BRACKETING TEST PART AT LEAST ONCE PER SHIFT

PHASE III RECOMMENDATIONS

CCAD NEAR-TERM IMPROVEMENTS — WOOLEY RIG OPERATIONS

- HAVE CCAD X NOZZLES MEASURED AT GE OR ALLISON USING THE AVRADCOM-ASME NOZZLES AS STANDARDS
- UTILIZE IMPROVED EQUATION TO CALCULATE PRODUCTION PART EFAs FROM CALIBRATED CCAD X REFERENCE NOZZLES
- VALIDATE BY MONITORING ENGINE REBUILD TEST CYCLE RESULTS

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PHASE III RECOMMENDATIONS

CCAD INTERIM IMPROVEMENTS

- REMOVE DOWNSTREAM CONE VALVE — EXHAUST TO AMBIENT PRESSURE
- PROVIDE WIDER RANGE OF UPSTREAM PRESSURES
- REWORK MANOMETER SYSTEM TO FULL RANGE
- CALIBRATE WOOLEY-RIG WITH FULL RANGE OF MEASURED CCAD X NOZZLE
- CHECK FOR ABILITY TO INTERPOLATE BETWEEN X REFERENCE NOZZLE EFAs

PHASE III RECOMMENDATIONS

CCAD

REPLACE WOOLEY RIG

- HIGHER THROUGHPUT
- LOWER COST
- IMPROVED ACCURACY
- IMPROVED CREDIBILITY

TECHNASSOCIATES INCORPORATED

FOLLOW-ON PROGRAM

AVRADCOM/CCAD/TI

- ACQUIRE COMMERCIAL AIRFLOW RIG
- INSTALL AT CCAD
- PREPARE CALIBRATION/PRODUCTION PROCEDURES
- TRAIN CCAD PERSONNEL
- MEASURE CCAD Xref NOZZLE EFAs
- CORRELATE TO WOOLEY RIG DATA
- PHASE-OUT WOOLEY RIG

FOLLOW-ON PROGRAM

AVRADCOM/CCAD/TI

- TOLERANCE LIMITS FOR NOZZLES
- PRODUCT SPECIFICATIONS/STANDARDS
- EXTENDED OPERATION vs "COLD" EFA
  EFA STABILITY = ?
- ENGINE TEARDOWN/REBUILD vs COMPRESSOR VARIATION
- RELIABILITY/PREDICTABILITY OF ENGINE PERFORMANCE ENVELOPE